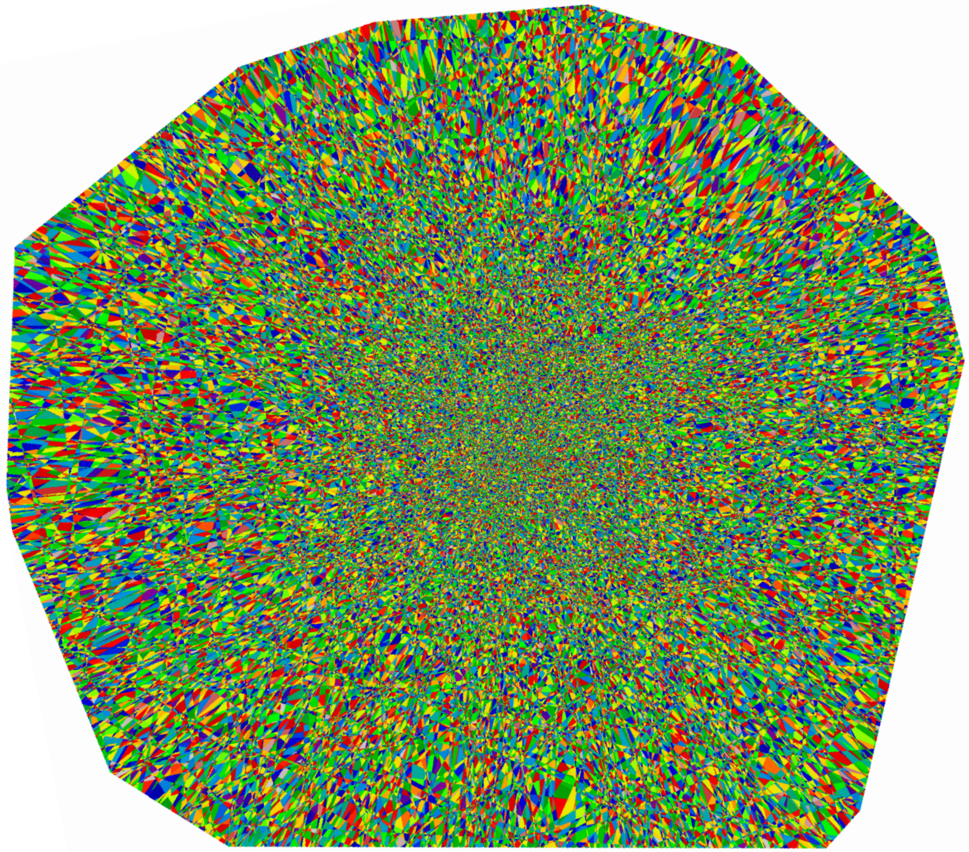
The Many Axions of String Theory



Liam McAllister

Cornell

Axions in Stockholm, July 1, 2025

The Many Axions of String Theory

Why does string theory have axions?

Antisymmetric tensor fields in six extra dimensions

Why *many* axions? How many?

Rich topology of extra dimensions. $N \sim 100$ to 100,000.

What are their properties?

Couplings scale with N.

Why does it matter what happens in string theory?

Axion couplings depend on nature of quantum gravity.

The Many Axions of String Theory

String theory has many axions because of the topological complexity of the six extra dimensions,

and the number N of axions *matters*:
large-N theories are qualitatively different from small-N theories.

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and the number N of axions *matters*:
large-N theories are qualitatively different from small-N theories.

We have, for the first time, constructed large-N theories in actual solutions of string theory.

We are in the process of discovering the properties of these theories.

Summary

Research program: computing the string axiverse,
the landscape of many-axion effective theories in string theory.

We have made advances in computational geometry allowing study of theories with $N \gg 1$ axions.

We have constructed part of the axiverse, in type IIB string theory on Calabi-Yau threefolds.

We find geometric hierarchies involving powers of N, and corresponding hierarchies in the low-energy couplings.

Consequences for strong CP, DM abundance, superradiance, axion-photon couplings.

We can already exclude many string models.

Based on

Demirtas, Long, L.M., Stillman 2018
'Kreuzer-Skarke Axiverse': C_4 axions in type IIB on CY_3

topological complexity
⇒ hierarchies

Mehta, Demirtas, Long, Marsh, L.M., Stott 2021
Black hole superradiance

Demirtas, Gendler, Long, L.M., Moritz 2021
Strong CP problem

Gendler, Marsh, L.M., Moritz 2023
Axion-photon couplings

Sheridan, Carta, Gendler, Jain, Marsh, L.M., Righi, Rogers, Schachner 2024
Fuzzy dark matter

consequences

Bellas, Halverson, L.M., Vander Ploeg Fallon, Zhu 2025
Axions in F-theory

many more axions
⇒ stronger effects


KING'S COLLEGE LONDON
SANCTE ET SAPIENTER
1829

Plan

I. Axions in string theory

II. Geometric hierarchies at $N \gg 1$

III. Hierarchies in axion couplings

Setting

We start with superstring theory,
for which the fundamental solution is $\mathbb{R}^{9,1}$.

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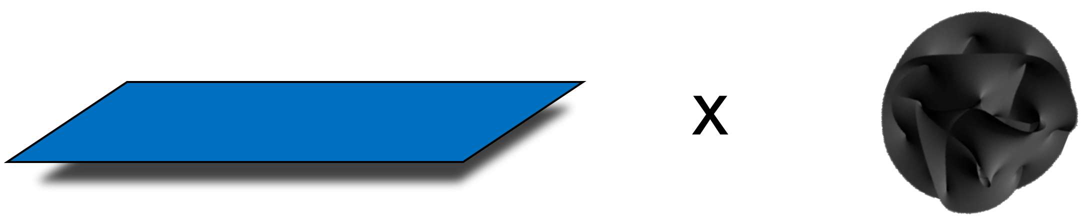
for which the fundamental solution is $\mathbb{R}^{9,1}$.

We study *compactifications* in the *geometric regime*:

$$ds^2_{10} = g^{(3+1)}_{\mu\nu} dx^\mu dx^\nu + ds^2_{X_6}$$

with X_6 a compact six-manifold that is large compared to a string.



4d spacetime   6d compact space

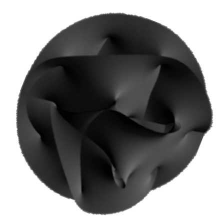
Geometry of the extra dimensions

Einstein equations in vacuum: $\textbf{Ricci} = 0$

$$R_{\mu\nu} = 0 \qquad \text{and} \qquad R_{mn} = 0$$

$$\mu, \nu \in \{0, 1, 2, 3\} \qquad m, n \in \{4, 5, 6, 7, 8, 9\}$$

x



4d spacetime

6d compact space

0123

456789

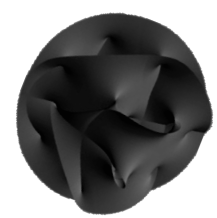
Geometry of the extra dimensions

Einstein equations in vacuum: $\mathbf{Ricci} = 0$

$$R_{\mu\nu} = 0 \qquad \text{and} \qquad R_{mn} = 0$$

Vacuum solution of string theory =
$\mathcal{M}^{3,1} \times$ [compact Ricci-flat six-manifold]
[e.g. ‘Calabi-Yau threefold’]

x



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Kaluza-Klein reduction

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + R^2 d\vartheta^2 \qquad \vartheta \cong \vartheta + 2\pi$$

Given a scalar Φ in 5d:

$$\Phi = \sum_n c_n \Phi_n(x^\mu, \vartheta)$$

$$\Phi_n(x^\mu, \vartheta) = \phi_n(x^\mu) \cdot \varphi_n(\vartheta) \qquad \varphi_n(\vartheta) = e^{in\vartheta}$$

$$0 = \Box_5 \Phi_n(x^\mu, \vartheta) \Leftrightarrow \left(\Box_4 + \frac{n^2}{R^2}\right)\phi(x^\mu) = 0$$

Massless 5d scalar Φ gives Kaluza-Klein tower of 4d scalars ϕ_n.
Massless 4d scalar from zero-mode φ_0.

In string theory it's the same, but with more extra dimensions.

Axions from extra dimensions

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + R^2 d\vartheta^2 \qquad \vartheta \cong \vartheta + 2\pi$$

Given a gauge field (1-form) A_M in 5d:

$$S_5 \supset -\int d^5x \, F_{MN} F^{MN} \,, \qquad M, N \in 0, \ldots 4$$

$$\theta := \int_0^{2\pi} d\vartheta \, A_4$$

$$S_4 \supset -\frac{1}{2} \int d^4x \, f^2 \partial_\mu \theta \partial^\mu \theta \,, \qquad f^2 = \frac{2}{\pi R^2}$$

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A 1-form A_1
integrated over a 1-manifold
yields an axion.

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + ds^2_{\mathrm{CY3}}$$

$$S_{10} \supset -\int d^{10}x \, F_{MNPQR} F^{MNPQR} \,, \qquad M, N \in 0, \dots 9$$

$$\theta_i := \int_{\Sigma_i} \left[dx^4 dx^5 dx^6 dx^7 \right] A_4$$

$$S_4 \supset -\frac{1}{2} \int d^4x \sum_i f_i^2 \partial_\mu \theta_i \partial^\mu \theta_i \,, \qquad f_i^2 \propto \mathrm{Vol}(\mathrm{CY}_3)^{-4/3}$$

A 4-form A_4
integrated over a 4-manifold
yields an axion.

In typical Calabi-Yau threefolds there are many submanifolds
$\Rightarrow$ many axion fields.

Setting

A **QGEFT** is an effective theory, of gravity and other fields, that results from an ultraviolet completion of gravity, such as a compactification of string theory.

Axion fields and couplings in QGEFT depend on topology, geometry, fields of extra dimensions.

We aim to understand axions in QGEFTs.

Strategy: enumeration of compactifications on Calabi-Yau threefolds (CY_3).

Context

Topologically simple compactifications yield simple QGEFTs.

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Topologically simple compactifications yield simple QGEFTs.

- No large dimensionless parameters. NDA works.

- Planck-suppressed operators have expected size:

  $\mathcal{L} \supset c_\Delta \frac{\mathcal{O}_\Delta}{M_{\rm pl}^{\Delta-4}}$ with $c_\Delta \gtrsim \mathcal{O}(1)$

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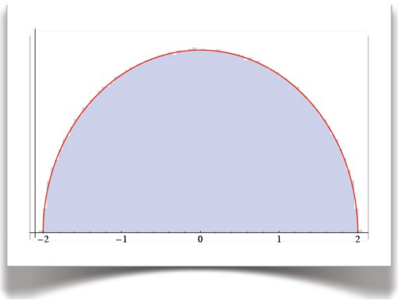
- e.g. $\mathcal{O} = \sum_{i,j=1}^{N} M_{ij}\phi^i\phi^j$.

Treating eigenvalues as $\sim$ equal numbers is too simple.

M.C.D. Marsh, L.M., Wrase 2011



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Enumerate compactifications of string theory at large N.

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Obstacle:

Until recently, topologically complex Calabi-Yau compactifications — those with $N \gg 1$ axions — were too complex to analyze.

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Kreuzer and Skarke, 2000

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Long, L.M., McGuirk 14
Long, L.M., Stout 16
Braun, Long, L.M., Stillman, Sung 17
Demirtas, Long, L.M., Stillman 18
Demirtas, Kim, L.M., Moritz 19
Demirtas, L.M., Rios-Tascon 20
Demirtas, Kim, L.M., Moritz 20
Mehta, Demirtas, Long, Marsh, L.M., Stott 21
Demirtas, Kim, L.M., Moritz, Rios-Tascon 21
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We have overcome this problem.

We found polynomial-time algorithms for 'everything', and implemented them in a software package, `CYTools`.

`Demirtas, L.M., Rios-Tascon 22`

`Long, L.M., McGuirk 14`
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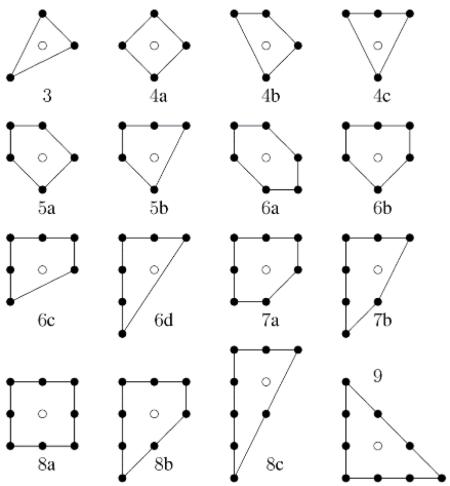
Combina-toric geometry

Key to unlocking large N:

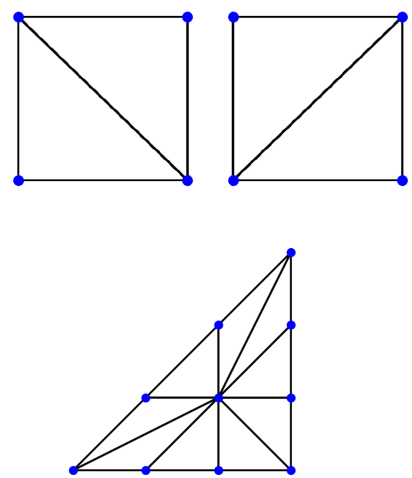
Constructing CY_3 as hypersurfaces in toric varieties, and exploiting combinatoric structures.

Toric varieties correspond to triangulations of polytopes.



473,800,776 4d reflexive polytopes

Kreuzer and Skarke 2000



$< 10^{428}$ CY_3

Demirtas, L.M., Rios-Tascon 2020

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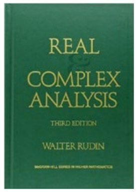
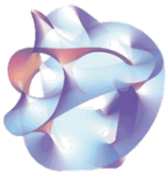


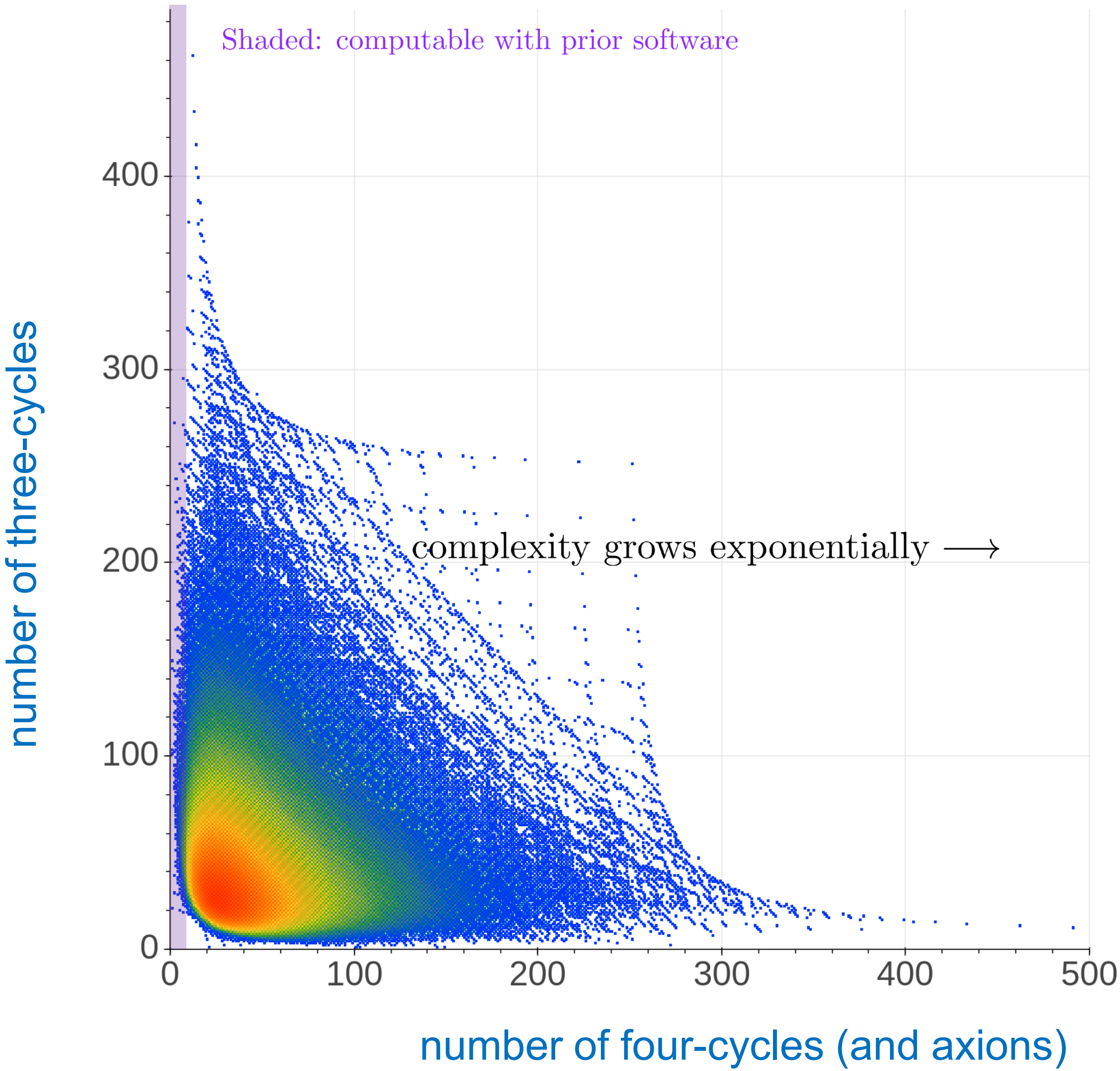
analysis



algebraic geometry

combinatorics

easier to automate

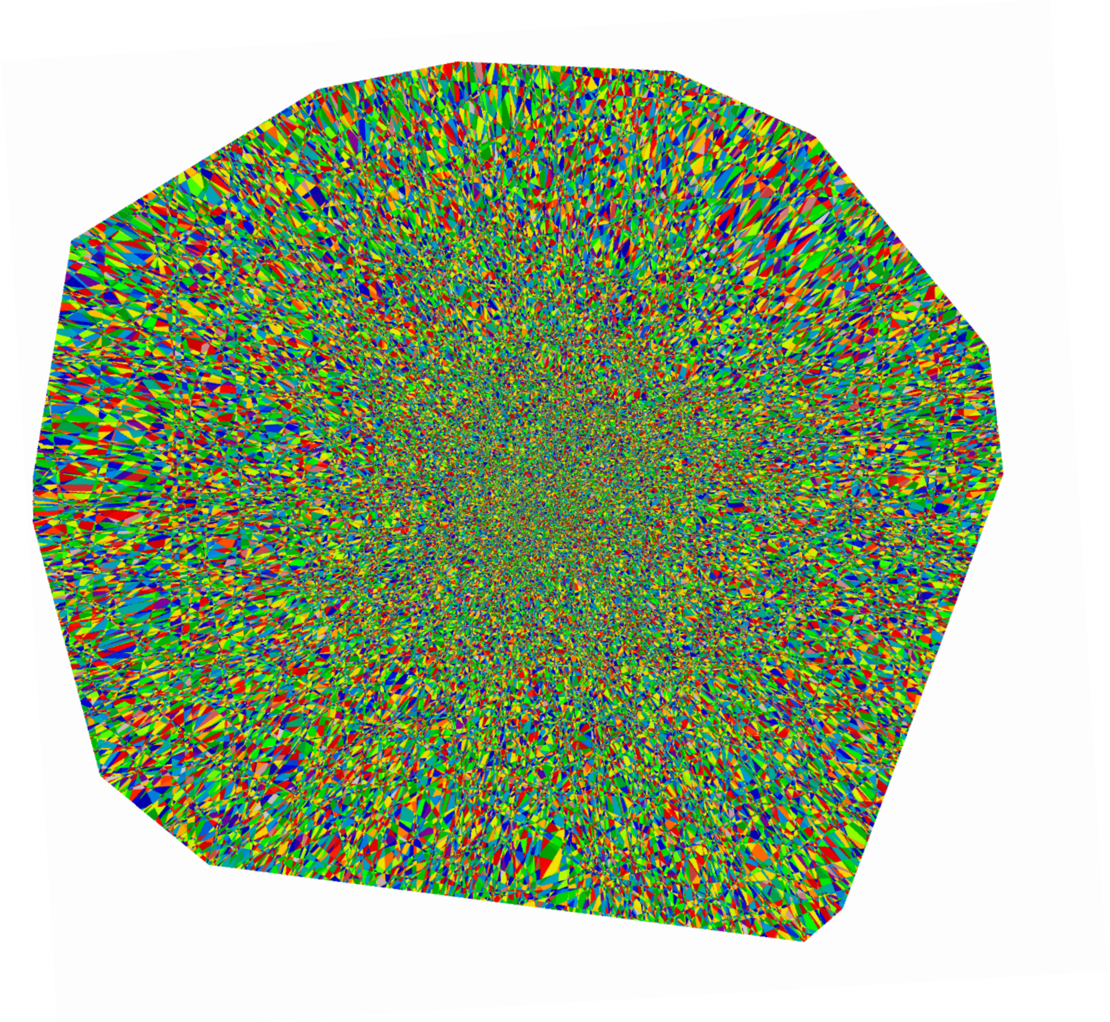


http://cy.tools

Demirtas, L.M., Rios-Tascon

The Kreuzer-Skarke Axiverse

Using `CYTools` we generated millions of CY_3 hypersurfaces.



The Kreuzer-Skarke Axiverse

Using `CYTools` we generated millions of CY_3 hypersurfaces.

Compactifying type IIB string theory, we constructed an ensemble of N-axion QGEFTs, $1 \leq N \leq 491$.

These are incarnations of the string axiverse.

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 09

Null hypothesis: isotropic internal space, one length scale L.

Our result: hierarchies of cycle sizes, polynomial in N.

Demirtas, Long, L.M., Stillman 2018

Topologically complex CY compactifications are anisotropic.

Consequence: hierarchical axion couplings.

Plan

I. Axions in string theory

II. Geometric hierarchies at $N \gg 1$

III. Hierarchies in axion couplings

Cycle sizes

Curvature expansion: a fundamental expansion in string theory.

Coupling ℓ_s/L. ℓ_s: string length
L: typical length

Can compute QGEFT when $\ell_s \ll L$.

Strategy: ensure that appropriate cycles are large in units of L.

Specifically: arrange that all 2-cycles have volume $> \ell_s^2$.

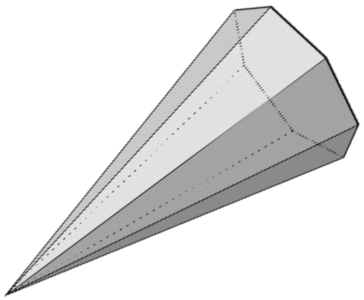
Let's see how to achieve this.

The Kähler cone

The number of 2-cycles is the number of axions, N.

So moduli space of 2-cycle sizes is $\subset \mathbb{R}^N$.

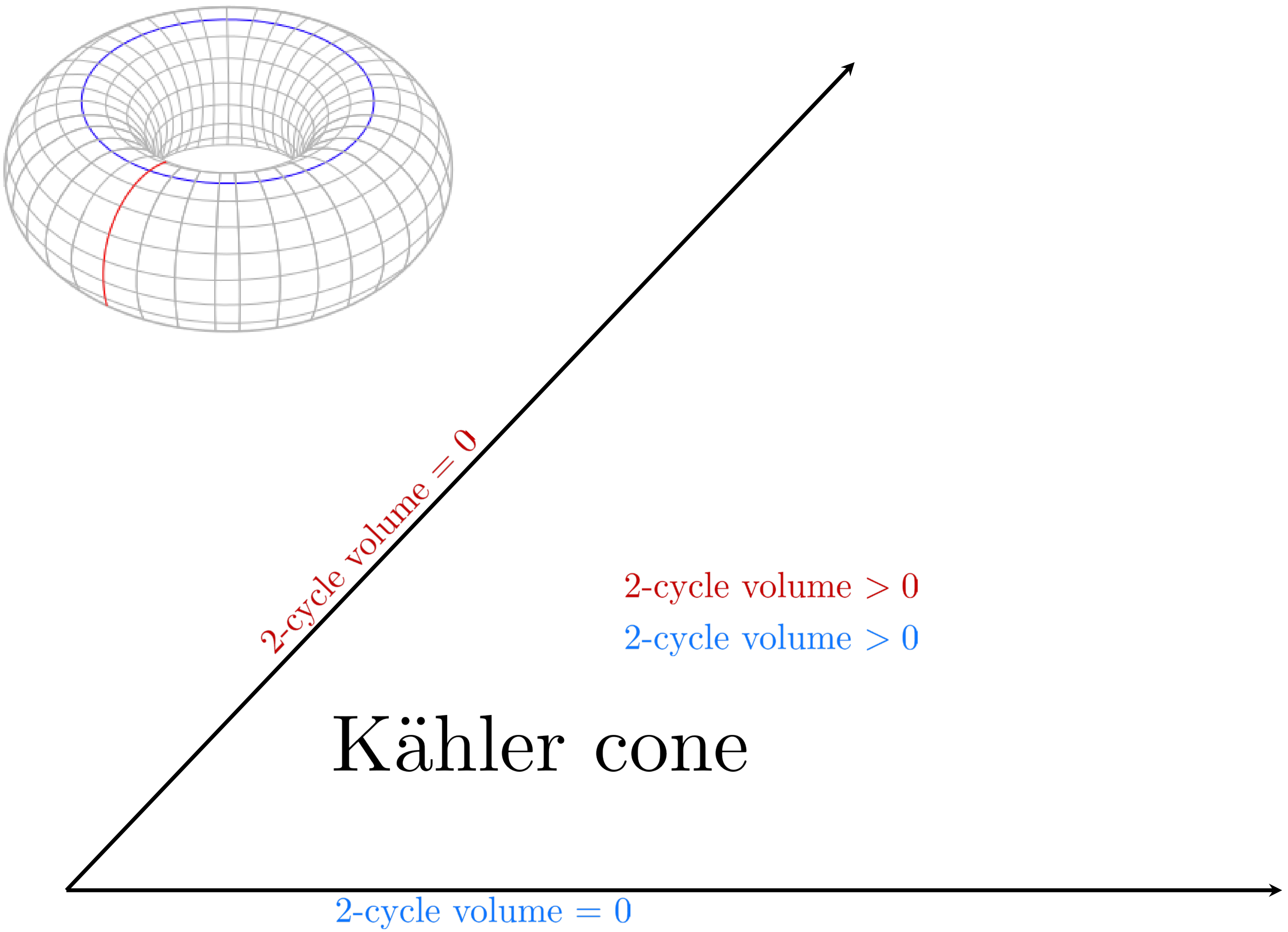
In fact it's a cone:



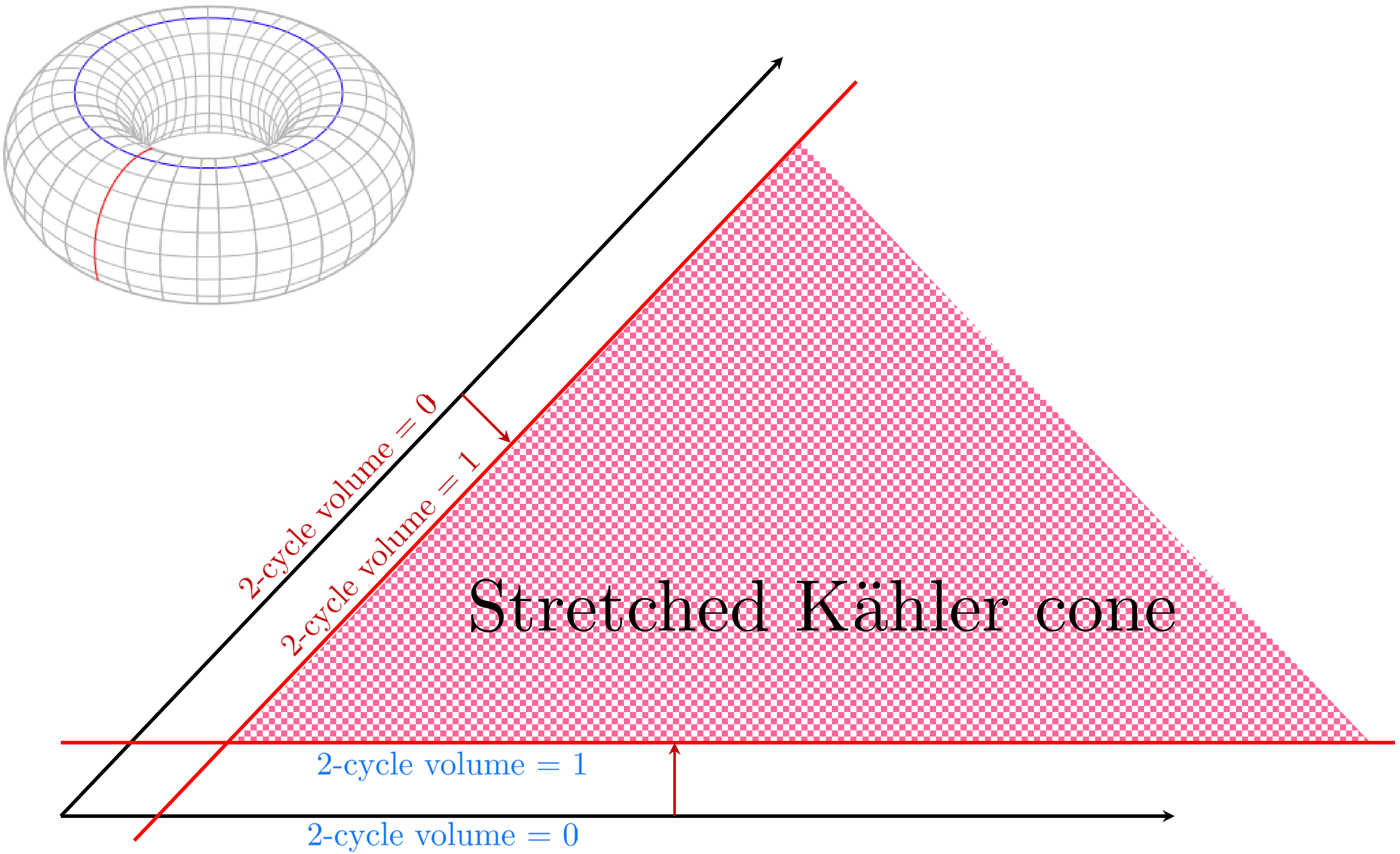
The *Kähler cone* $\mathcal{K} \subset \mathbb{R}^N$
is the region where all 2-cycles have volume ≥ 0.

On the walls of the cone, one or more 2-cycles have zero size.
Inside the cone, all (holomorphic) 2-cycles have positive size.

The Stretched Kähler cone
is the subregion of $\mathcal{K}$ where all 2-cycles have volume ≥ 1.



2-cycle volume = 0
2-cycle volume > 0
2-cycle volume > 0
Kähler cone
2-cycle volume = 0



We work in the stretched Kähler cone,
where the curvature expansion is plausibly controlled.

Key observation

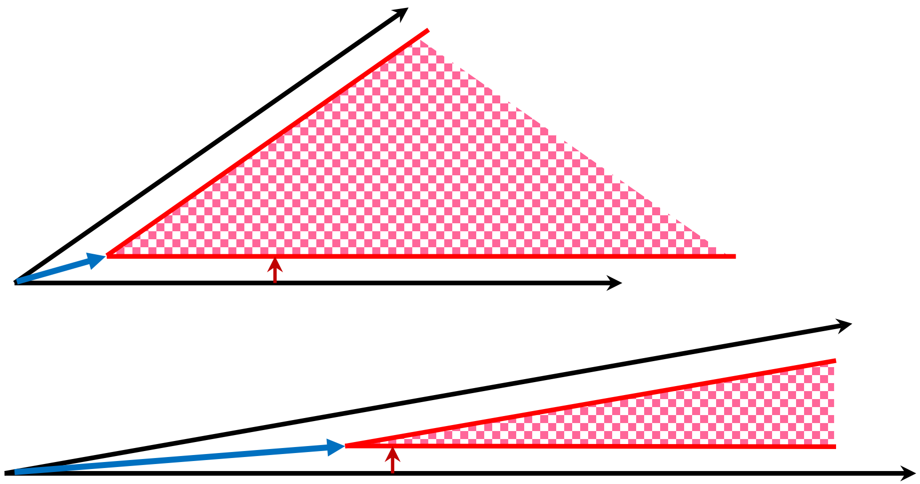
In a narrow cone with many walls,
the subcone that is distance ≥ 1 from every wall
has its apex far from the origin.

Fact: for $N \gg 1$, Kähler cones are narrow and have many walls.

So for $N \gg 1$, stretched Kähler cones have apex far from the origin.

This means that some cycles are large.

Their size is a power of N.



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So for $N \gg 1$, stretched Kähler cones have apex far from the origin.

This means that some cycles are large.

Their size is a power of N.

But other cycles have volumes of order unity.

A main result: hierarchies of cycle sizes, by powers of N.

'Topologically complex CY compactifications are anisotropic'.

Key observation

Consider a spherical cow of radius R_{cow}.

Q: find minimum R_{cow} s.t. all its spots have size $R_{\text{spot}} > 1$ meter.

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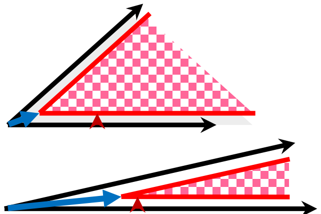
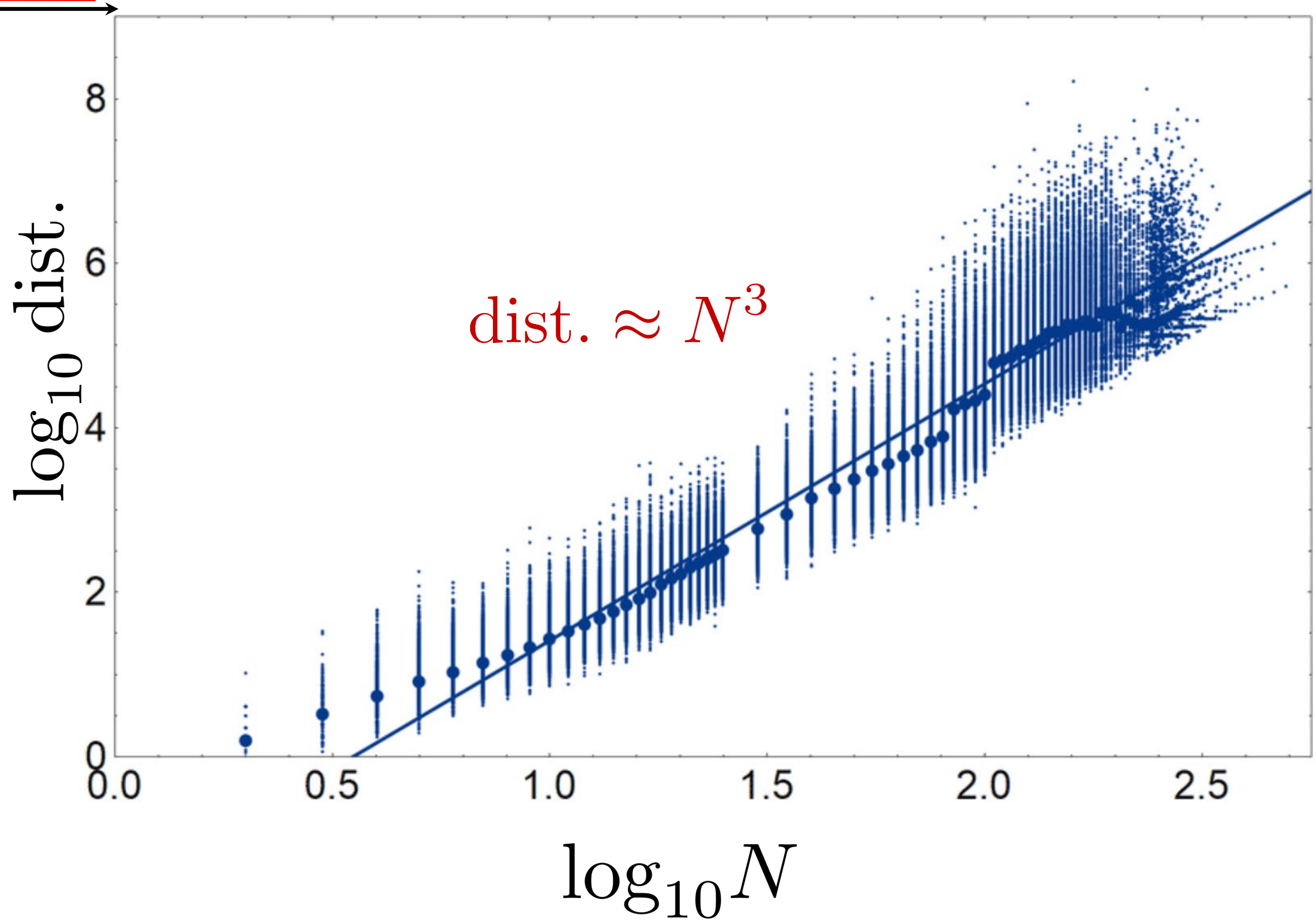
A1: For an isotropic cow, $R_{\text{cow}} \sim R_{\text{spot}}$, so $R_{\text{cow,min}} \sim 1$.

A2: For an *anisotropic cow with many spots of widely varied size*, one has $R_{\text{cow,min}} \gg 1$.

CY_3 are anisotropic, with many cycles of widely varied size.

Distance to tip of cone





Story so far

We constructed a landscape of string compactifications, and studied the resulting many-axion theories.

We found geometric hierarchies that are powers of the number of axions, N.

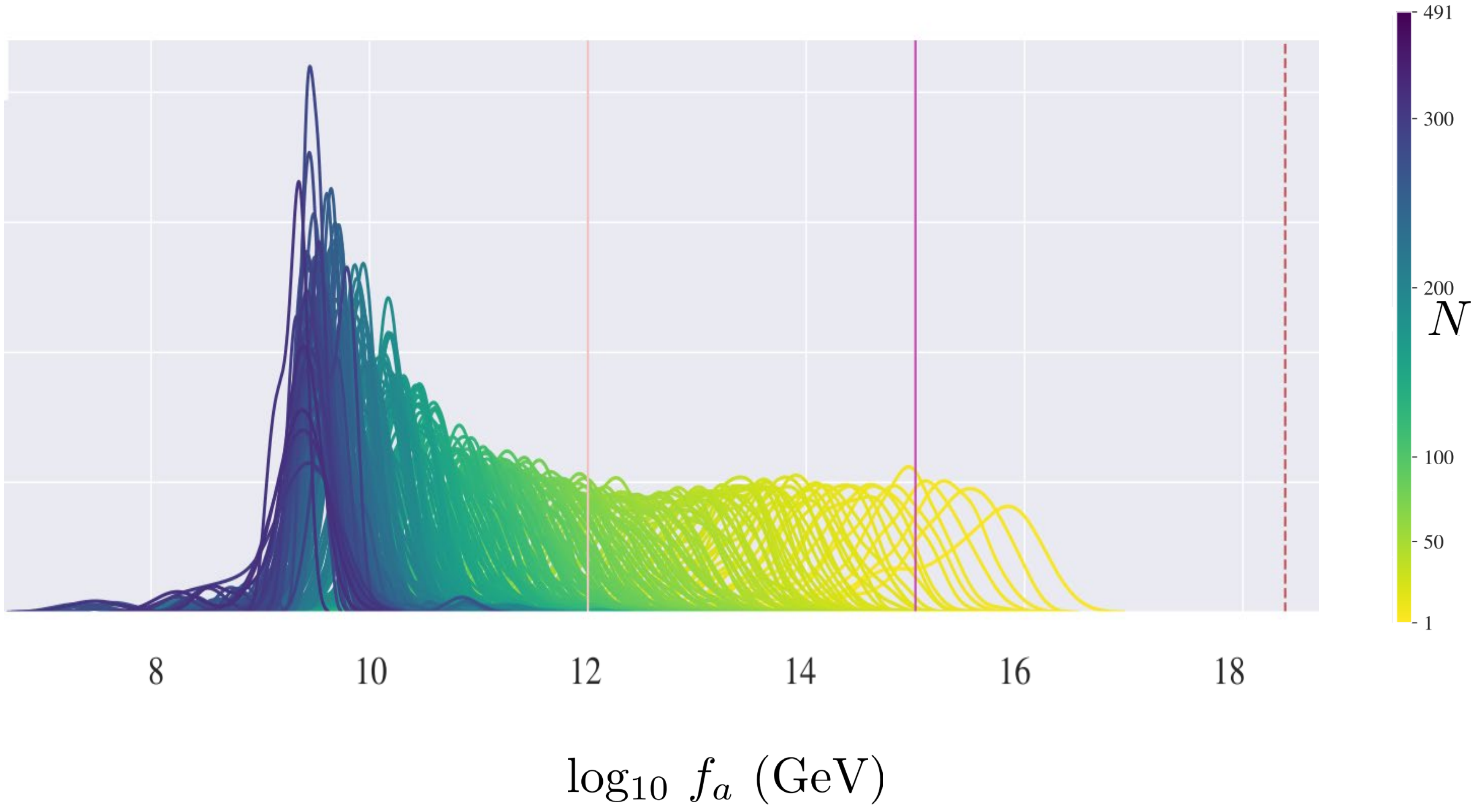
Next: the geometric hierarchies lead to hierarchies in the low-energy couplings, with consequences for phenomenology.

Warning: not clear that these extra-dimensional axions can form axion strings.

Consequence #1:

Decay constants spread over wide range, and diminish with N.

Decay constants f_a



Consequence #2:

Fuzzy axion dark matter is extremely rare for $N \gtrsim 15$.

Sheridan, Carta, Gendler, Jain, Marsh, L.M., Righi, Rogers, Schachner 2412.12012

Fuzzy axion dark matter

Could dark matter consist of ultralight axions?

For $m_a \lesssim 10^{-18}\,\text{eV}$, chance of future tests.

For $m_a \sim 10^{-21}\,\text{eV}$, significant constraints.

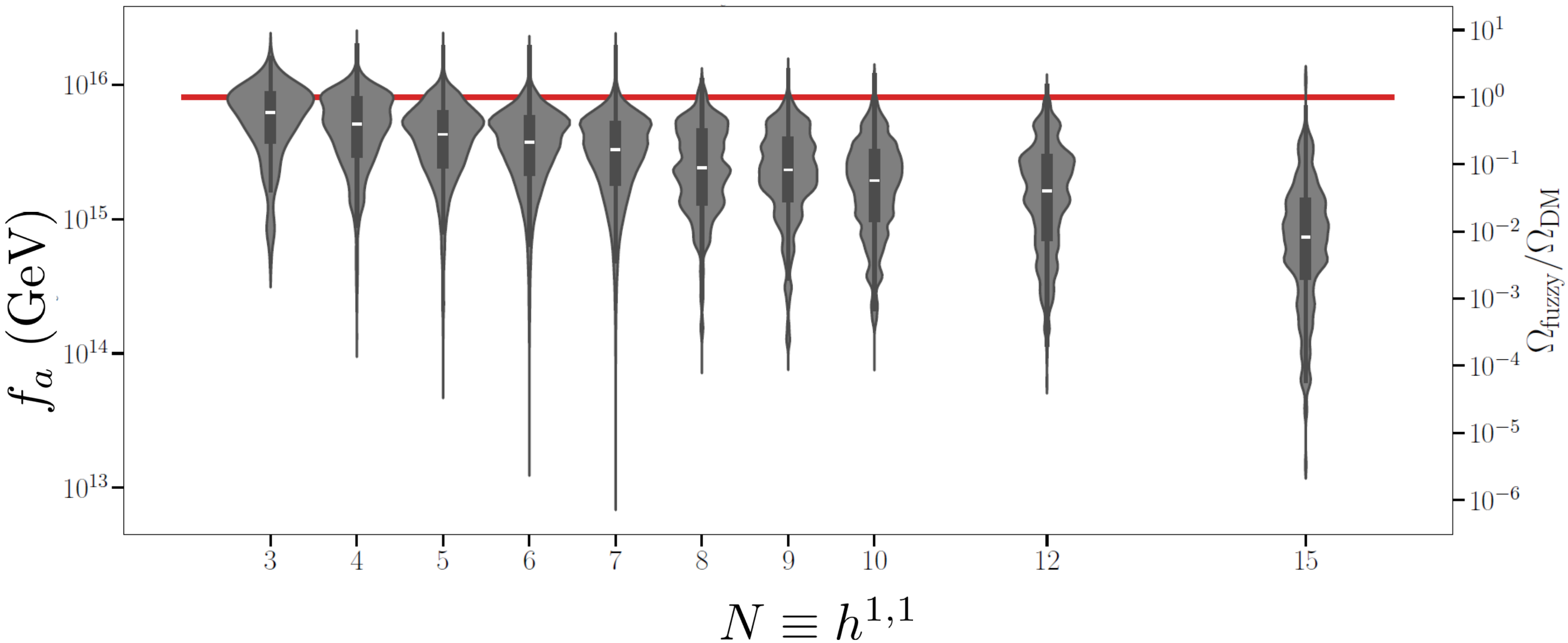
Misalignment abundance $\Omega_a \propto f_a^2 \sqrt{m_a}$.

$\Rightarrow$ need $f_a \gtrsim 10^{16}\,\text{eV}$ for abundant fuzzy axion DM.

We find f_a decreases with N,
and is typically too small for fuzzy DM for $N \gtrsim 15$.

Sheridan, Carta, Gendler, Jain, Marsh, L.M., Righi, Rogers, Schachner 2412.12012
cf. Cicoli, Guidetti, Righi, Westphal 21

Fuzzy axions at small N



f_a typically too small for fuzzy DM for $N \gtrsim 15$.

Fuzzy DM generally accompanied by overabundance of heavier-axion DM. Exceptions: fibration, or tuned cosmology.

Sheridan, Carta, Gendler, Jain, Marsh, L.M., Righi, Rogers, Schachner 2412.12012

Consequence #3:

Strong CP problem solved by PQ mechanism,
without a PQ quality problem,
for $N \gtrsim 15$.

Demirtas, Gendler, Long, L.M., Moritz, 2112.04503

PQ quality problem

The Peccei-Quinn solution of the strong CP problem is sensitive to Planck-scale CP-breaking, and so requires UV completion. This is the *PQ quality problem*.

High-scale physics, even Planck-scale physics,
can easily break PQ symmetry badly enough to ruin mechanism.

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If there is another term that breaks the PQ shift symmetry,

$$\text{e.g.} \qquad V_{\text{breaking}} = \Lambda^4 \cos(\bar{\theta} + \psi) \qquad \psi \in [0, 2\pi)$$

$$\text{then} \qquad \langle \bar{\theta} \rangle \sim \frac{\Lambda^4}{\Lambda_{\text{QCD}}^4} \lesssim 10^{-10} \quad \Leftrightarrow \quad \Lambda^4 \lesssim 6 \times 10^{-14}\ \text{GeV}^4$$

Write in terms of $\Lambda^4 \equiv M_{\text{pl}}^4 e^{-S}$ as

$$S \gtrsim 200.$$

So *every instanton carrying PQ charge* must have $S \gtrsim 200$.

PQ quality problem

Every instanton carrying PQ charge must have $S \gtrsim 200$.

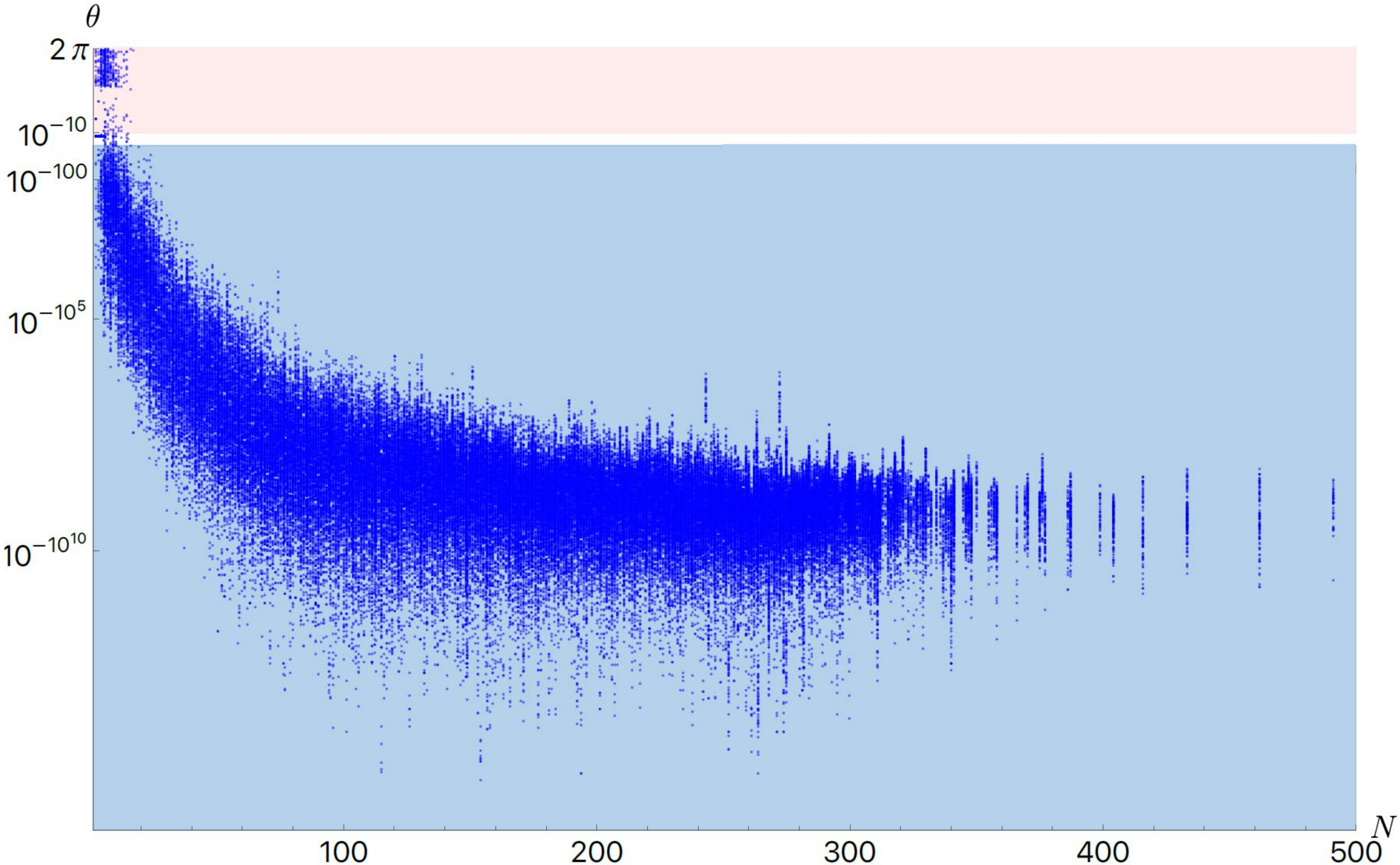
This dramatic sensitivity to Planck-scale physics is an opportunity for string theory: the effects in question can be computed.

In our ensemble this breaking comes from certain instantons.

We explicitly compute the leading such instantons.

When $N \gtrsim 15$, the Planck-scale breaking is negligible, and the quality problem is solved.

PQ quality

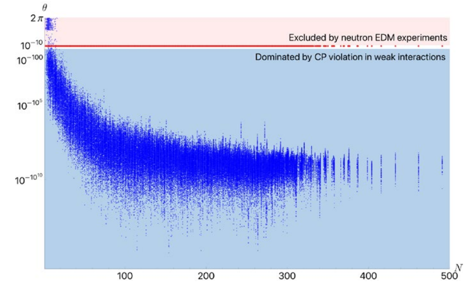


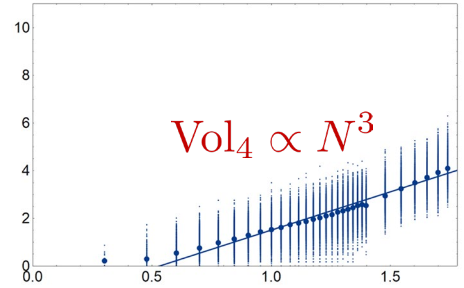
Demirtas, Gendler, Long, L.M., Moritz, 2112.04503

PQ quality problem in string theory

What's going on:

$\Delta\theta \propto e^{-2\pi \mathrm{Vol}_4}$, for leading 4-cycle.





Anisotropy of topologically complex space
$\Rightarrow$ large 4-cycles
$\Rightarrow$ small θ-angle.

Demirtas, Gendler, Long, L.M., Moritz, 2112.04503

Consequence #4:

Photon couplings to ultralight axions
are hierarchically suppressed,
if there is a stringy instanton on the QED cycle.

Gendler, Marsh, L.M., Moritz 23

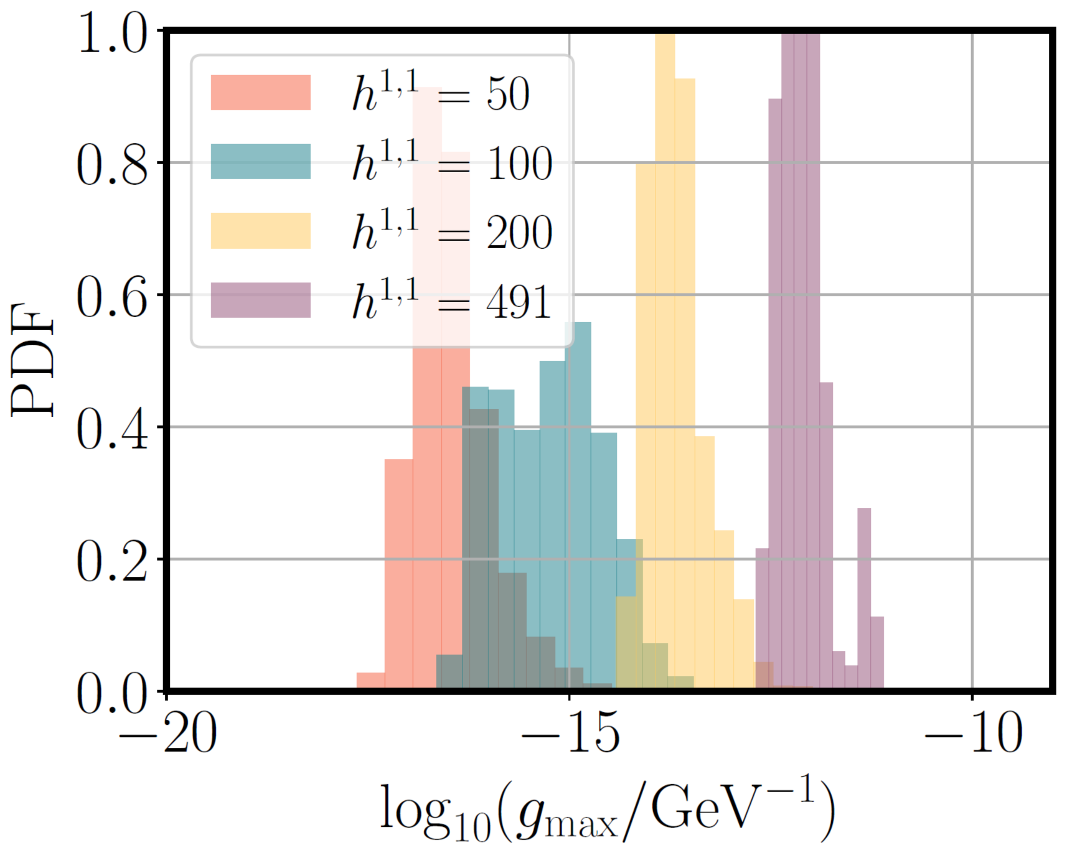
Axion-photon couplings

$$\mathcal{L}_{\mathrm{QED}} = -\frac{1}{4} g_{a\gamma\gamma}\, \varphi^a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

We have not built actual SM.
QED proxy: 4-cycle Σ_{QED} that 'could' host QED.

$g_{a\gamma\gamma} \sim 1/f \Rightarrow$ coupling increases with N

Axion-photon couplings



$g_{a\gamma\gamma} \sim 1/f \Rightarrow$ coupling increases with N

Gendler, Marsh, L.M., Moritz 23

Light threshold

Gauge group with θ-angle $\mathcal{L}_{\text{gauge}} = \theta_a \, F_{\mu\nu} \tilde{F}^{\mu\nu}$

and potential $\mathcal{L} \supset \Lambda^4 \cos(\theta_a)$ $\varphi_a = \theta_a / f_a, \quad a = 1, \ldots, N$

has negligible coupling to axions φ_j with $m_j \ll m_{\text{gauge}} \equiv \Lambda^2 / f_a$.

QED does not have ordinary instantons of its own.

But there can be stringy instantons!

Then the photon has negligible couplings to axions j with

$$m_j \ll m_{\text{light}} \equiv f_{\text{QED}}^{-1} \, e^{-2\pi \text{Vol(QED)}}$$

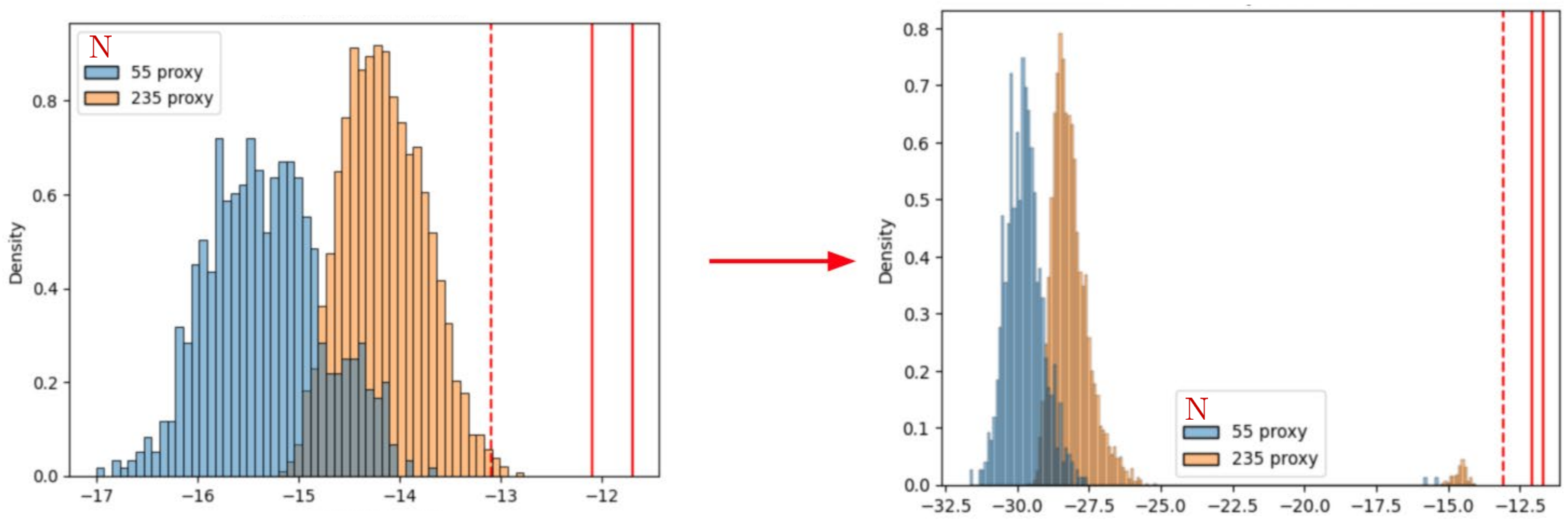
Light threshold: a mass scale set by stringy instantons on Σ_{QED}.

Axions with $m \ll m_{\text{light}}$ have negligible photon couplings.

Makes ultralight axions invisible.

Gendler, Marsh, L.M., Moritz 23

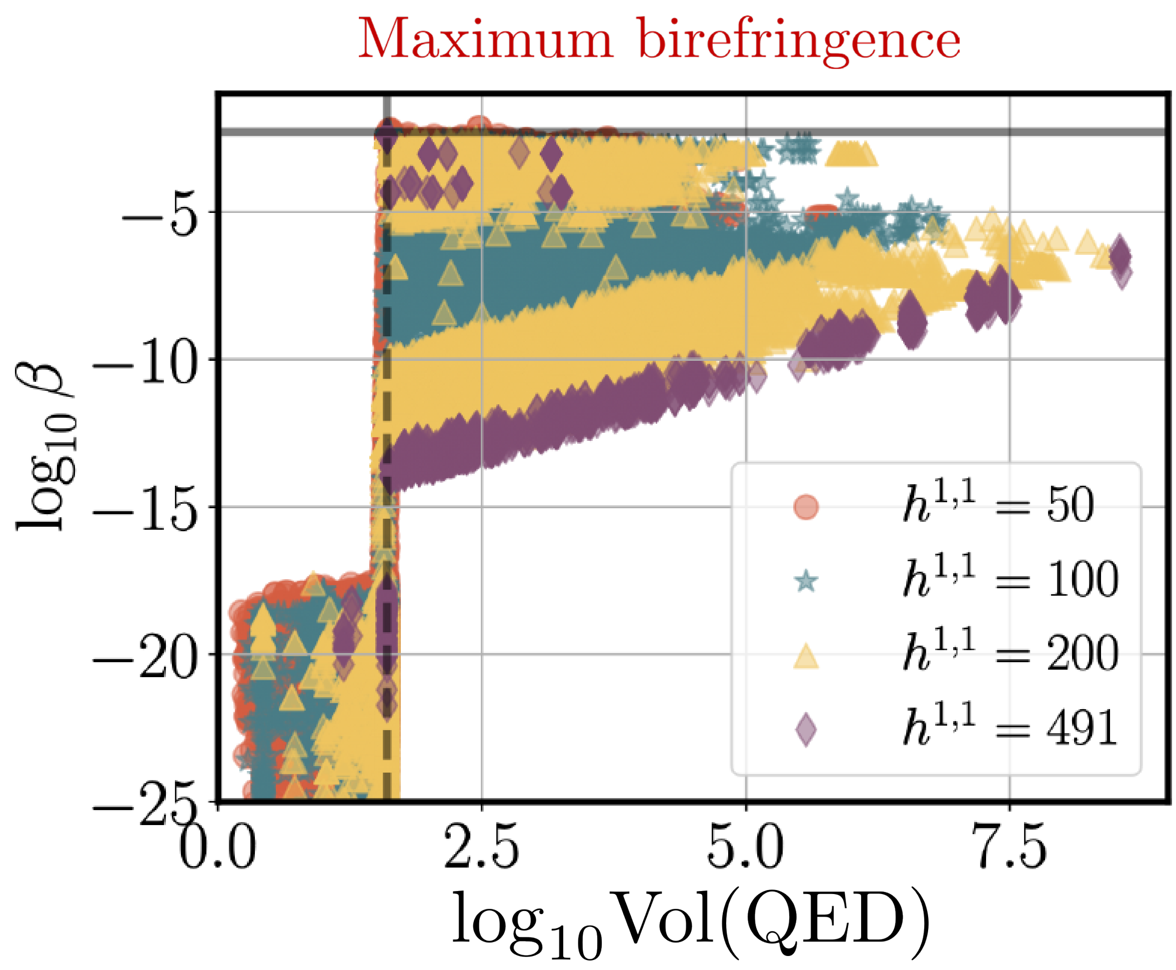
Light threshold



Bellas, Halverson, L.M., Vander Ploeg Fallon, Zhu WIP

Gendler, Marsh, L.M., Moritz 23

Birefringence prospects



$\beta \approx 0.3^\circ$ possible for Vol(QED) ≈ 40.

Minami, Komatsu 20

Coincidentally, $\alpha^{-1} \approx \frac{1}{40}$ at GUT scale in SM.

Gendler, Marsh, L.M., Moritz 23

F-theory axiverse

So far, the string axiverse. Now, a work in progress: F-theory.

F-theory = type IIB string theory with strong + varying coupling

Compactify F-theory on a CY_4 that is a fibration over a base B_3.

In general B_3 is not a CY_3.

Consequence: much wider range of possible topologies.

String theory on CY_3: $N \leq 491$.

F-theory on CY_4: $N \leq 181{,}820$. Wang 2020

best-understood ensemble: $N \leq 2{,}591$ Halverson, Long, Sung 17

Bellas, Halverson, L.M., Vander Ploeg Fallon, Zhu WIP

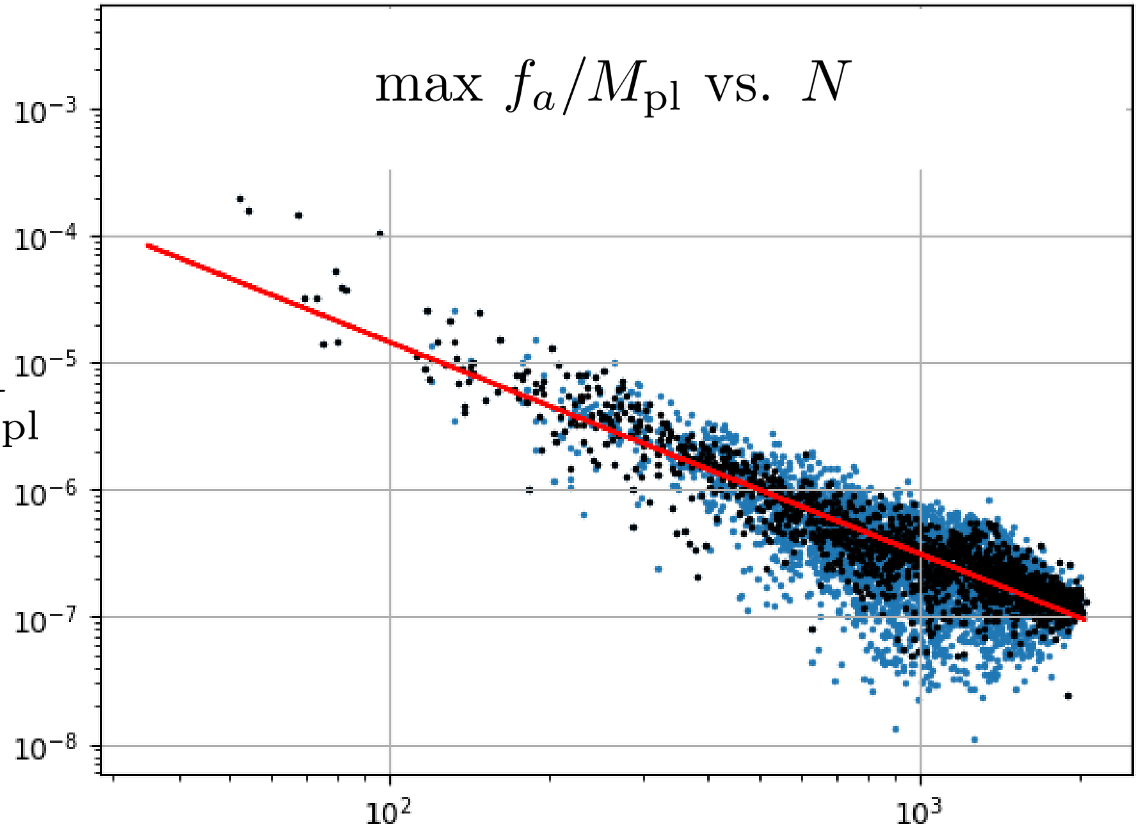
F-theory axiverse

'Tree' ensemble, of toric threefold bases. $N \leq 2{,}591$

cf. Halverson, Long, Sung 17

Result: trends seen in CY_3 ($N \leq 491$) continue for $N \leq 2{,}591$.

max $f_a/M_{\rm pl}$



N

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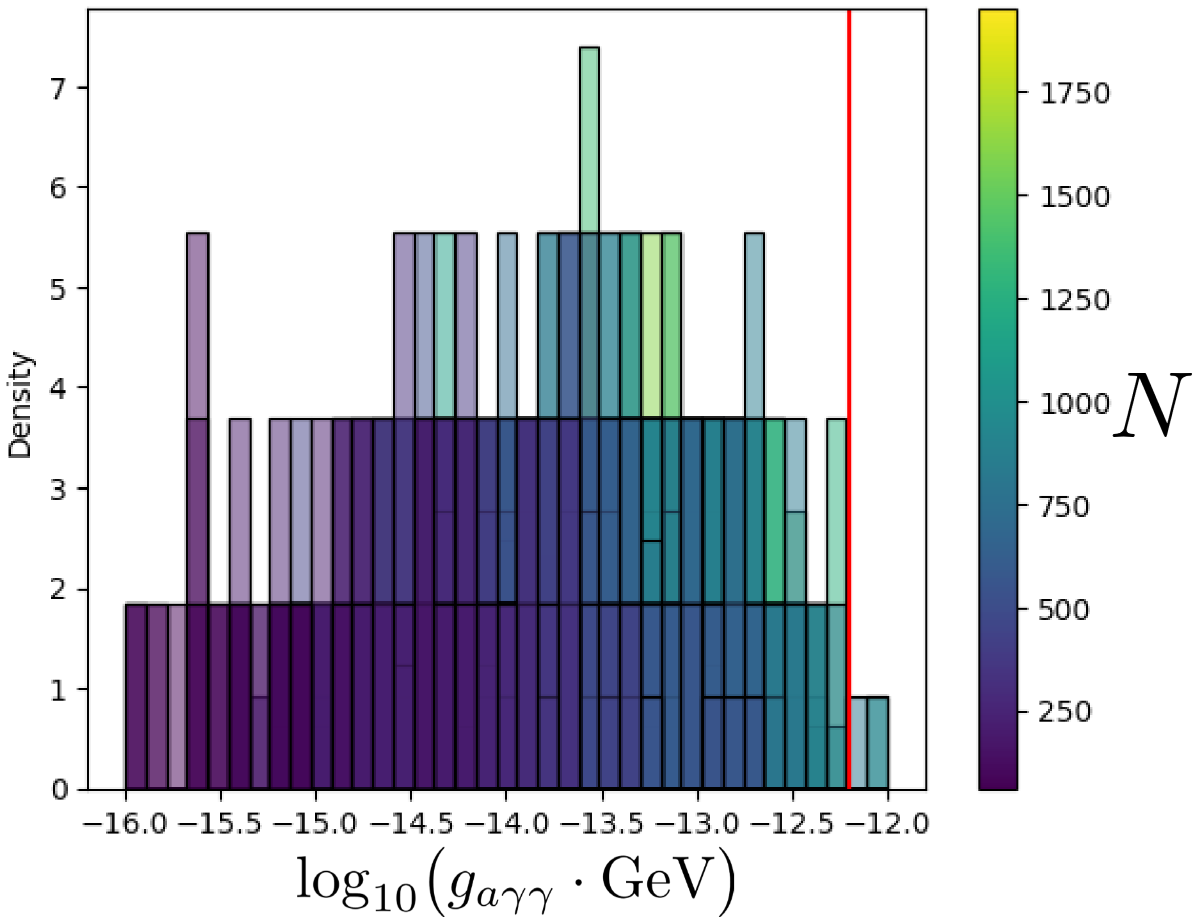
F-theory axiverse

Result: $g_{a\gamma\gamma}$ increases with N.
Here: preliminary first sample up to $N \leq 2{,}591$.



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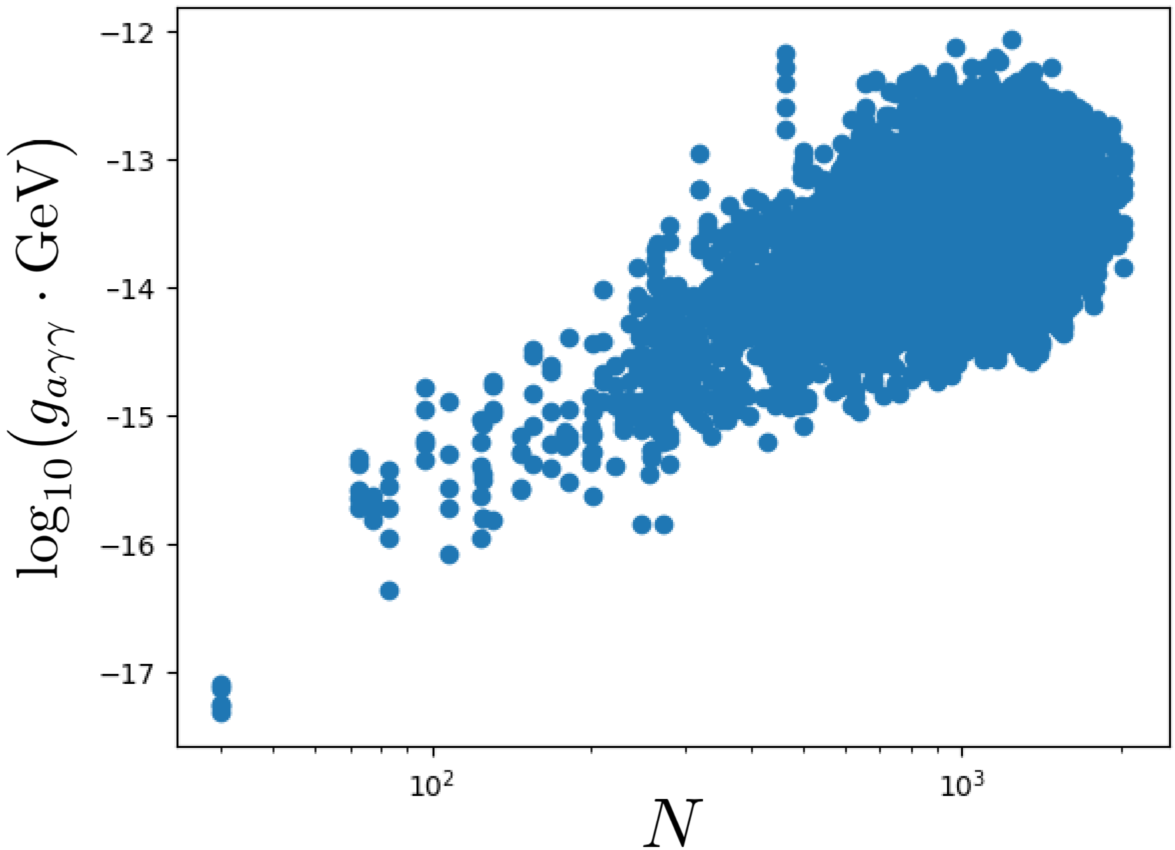


Models exist up to $N = 181{,}820$.

Bellas, Halverson, L.M., Vander Ploeg Fallon, Zhu WIP

Conclusions and Outlook

Advances in computational geometry have allowed us to construct parts of the string axiverse, with $N \gg 1$.

Geometric hierarchies from control of curvature expansion lead to hierarchies of couplings in the axion EFT.

Expect progress in:

- explicit SM constructions and couplings
- other string theories, other compactifications
- F-theory, with N up to 180,000
- moduli stabilization
- models of inflation and reheating
- detailed constraints

Thanks!

Axion couplings

N axions: $$\theta^a := \int_{a^{th}\,\text{4-cycle},\ \Sigma_a} C_4 \qquad a = 1, \ldots, N$$

$$\mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{pot}} + \mathcal{L}_{\text{gauge}}$$

$$\mathcal{L}_{\text{kin}} = -\frac{1}{2}\mathcal{K}_{ab}\partial\theta^a\partial\theta^b$$

metric $\mathcal{K}_{ab}$: volumes, intersection numbers

$$\mathcal{L}_{\text{pot}} = -\sum_{\text{instantons},\ I} \Lambda_I^4\left[1 - \cos\left(Q^I{}_a\,\theta^a\right)\right]$$

scales Λ_I: 4-cycle volumes

charges $Q^I{}_a$: topology

$$\mathcal{L}_{\text{gauge}} = \sum_{\text{gauge groups},\ A} C_a{}^A\,\theta^a (F_{\mu\nu}\tilde{F}^{\mu\nu})_A$$

gauge groups: D-branes

couplings $C_a{}^A$: topology

Computable in terms of topology and point in moduli space.

Turn the crank

1. Construct ensemble of CY_3 hypersurface topologies.

2. Sample moduli space inside stretched Kähler cone.

3. Specify (or model) D-brane configuration.

4. Identify contributing instantons.

5. Compute axion couplings.

6. Express in terms of mass+kinetic eigenstates.

Canonical axion couplings

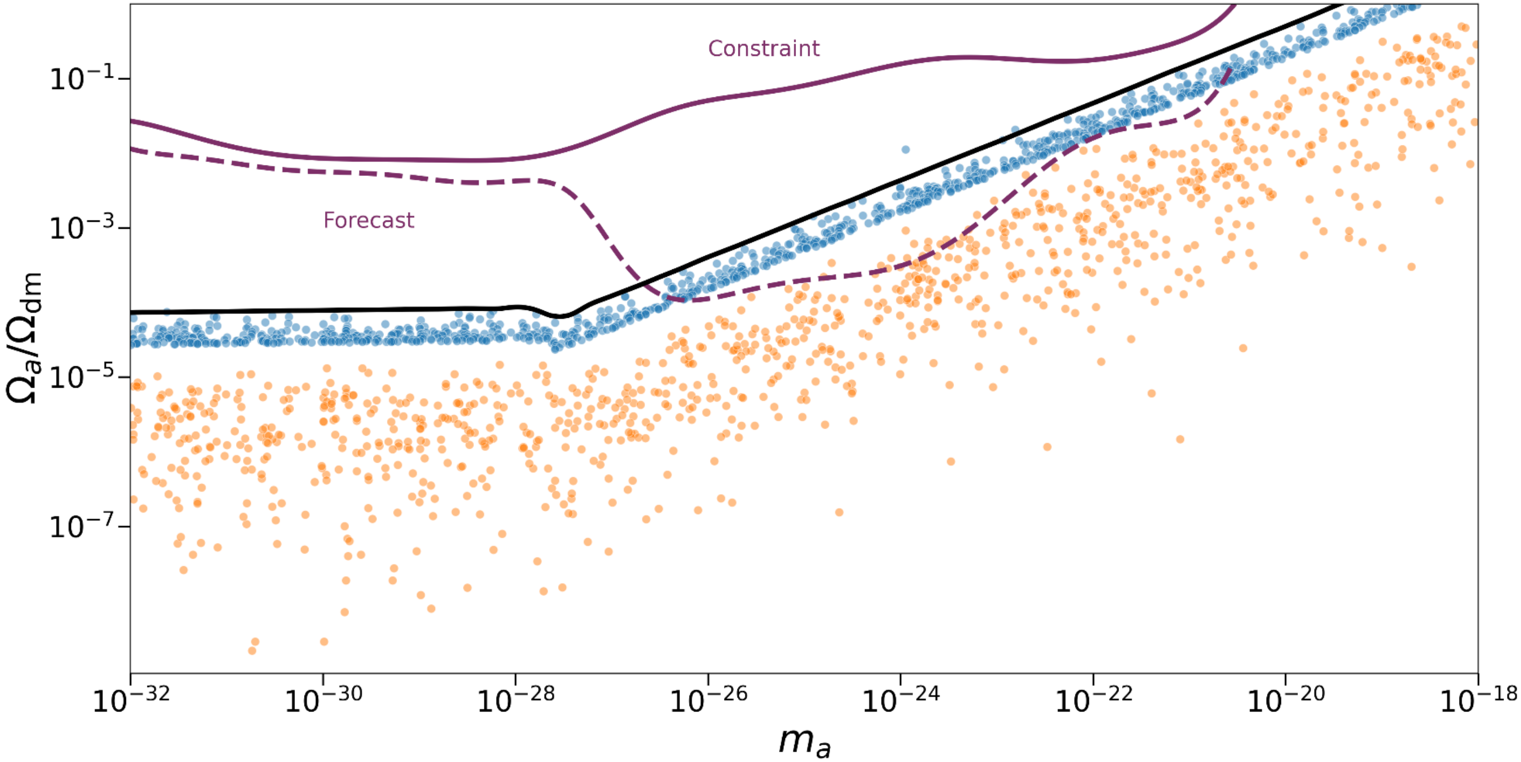
$$\mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{mass}} + \mathcal{L}_{\text{gauge}} + \ldots$$

$$\mathcal{L}_{\text{kin}} = -\frac{1}{2}\sum_a \left(\partial\varphi^a\right)^2$$

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\sum_a m_a^2(\varphi^a)^2 \qquad\qquad m_a^2 = \frac{\Lambda_a^4}{f_a^2}$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\sum_{\text{groups, A}} g_{a\gamma^A\gamma^A}\,\varphi^a(F_{\mu\nu}\tilde{F}^{\mu\nu})_A$$

Fuzzy axion abundance



Sheridan, Carta, Gendler, Jain, Marsh, L.M., Righi, Rogers, Schachner 2412.12012